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GEOMORPHOLOGICAL PROBLEMS OF THE MIDDLE REACHES OF THE TSANGPO RIVER, TIBET

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ABSTRACT

The middle reaches of the Tsangpo River consist of alternating sections of wide valleys and gorges. The wide valley sections have braided and anastomosing channels, gentle hydraulic gradients, thick alluvial deposits and low terraces. In contrast, the gorge sections exhibit single, straight and deeply entrenched meandering channels with steep hydraulic gradients, bare rock river beds and higher terraces. Several hypotheses have been used to explain these unusual fluvial landforms, but geological, landform and sedimentary analyses along with dating information, suggest that the key could be the active faults across the river valley.

All gorge sections are located on the upthrown side of active faults, which mainly occurred in or after the Pliocene, whilst the wide valley sections appear on the downthrown side. The faulting blocked the river and caused the formation of palaeolakes, with thick deposits laid down behind the faults. Therefore, depositional wide valleys were formed and old terraces were buried. On these downthrown sides of the faults, braided and anastomosing channels have developed. On the upthrown sides, strong incision of the river occurred because of the changes of the local base levels and river gradients. As a result, deep gorges and deeply entrenched meandering channels formed in various lithologies. The terraces on the gorge slope indicate different stages of river incision and the related knick points appeared close to the local active faults. Rock resistance is only a minor influence on the alternation of valley forms and river gradients in this area.

KEY WORDS: Tsangpo River; Yaluzangbu; Brahmaputra; Tibet; Fluvial geomorphology; landform

INTRODUCTION

The Tsangpo (Yaluzangbu, Sangpo, Yarlutsangpo, Yarluzhangpo or the upstream section of the Brahmaputra) River originates from the Jimayangzhong Glacier on the northern slope of the Himalayas and flows eastward, then turns suddenly southward at 95°E to become the Brahmaputra (Figure 1). From its source to the border between China and India, the river has a length of 2091 km with a catchment area of 238 000 km^2 and an average discharge of 4425 $m^3 s^{-1}$ (TETCAS, 1983). Its middle and upper course is above 2800 m a.s.l.. The boundaries of the drainage basin of the middle reach are high mountain ranges, the Himalayas in the south and the Gandise Mountains in the north. The catchments of the main stream are quite asymmetric, being wider and larger to the north. Glacial meltwater from these high mountains is one of the major sources of the river. The hydraulic gradient of the middle reach of the Tsangpo surprised many early explorers. Colonel Montgomerie in 1896 wrote: ‘The navigation at 13 500 feet above the sea, rude though it may be, is an extraordinary feat’. This refers to relatively gentle hydraulic gradients in the upper and middle reaches. However, detailed investigation of fluvial landforms shows that the whole middle stream course consists of sections with wide valleys and gorges, which accompany gentle and steep gradients. Within the middle section of the drainage system, the annual average precipitation increases remarkably downstream, from 200 mm upstream to 900 mm at Pai. This precipitation gradient is due to the southwest Indian monsoon that breaks into the plateau through the valley and gradually loses its moisture upstream. The river has ten major tributaries that are over 100 km in length. Their valley form depends on that of the main course. In the middle reach, braided, free meandering and

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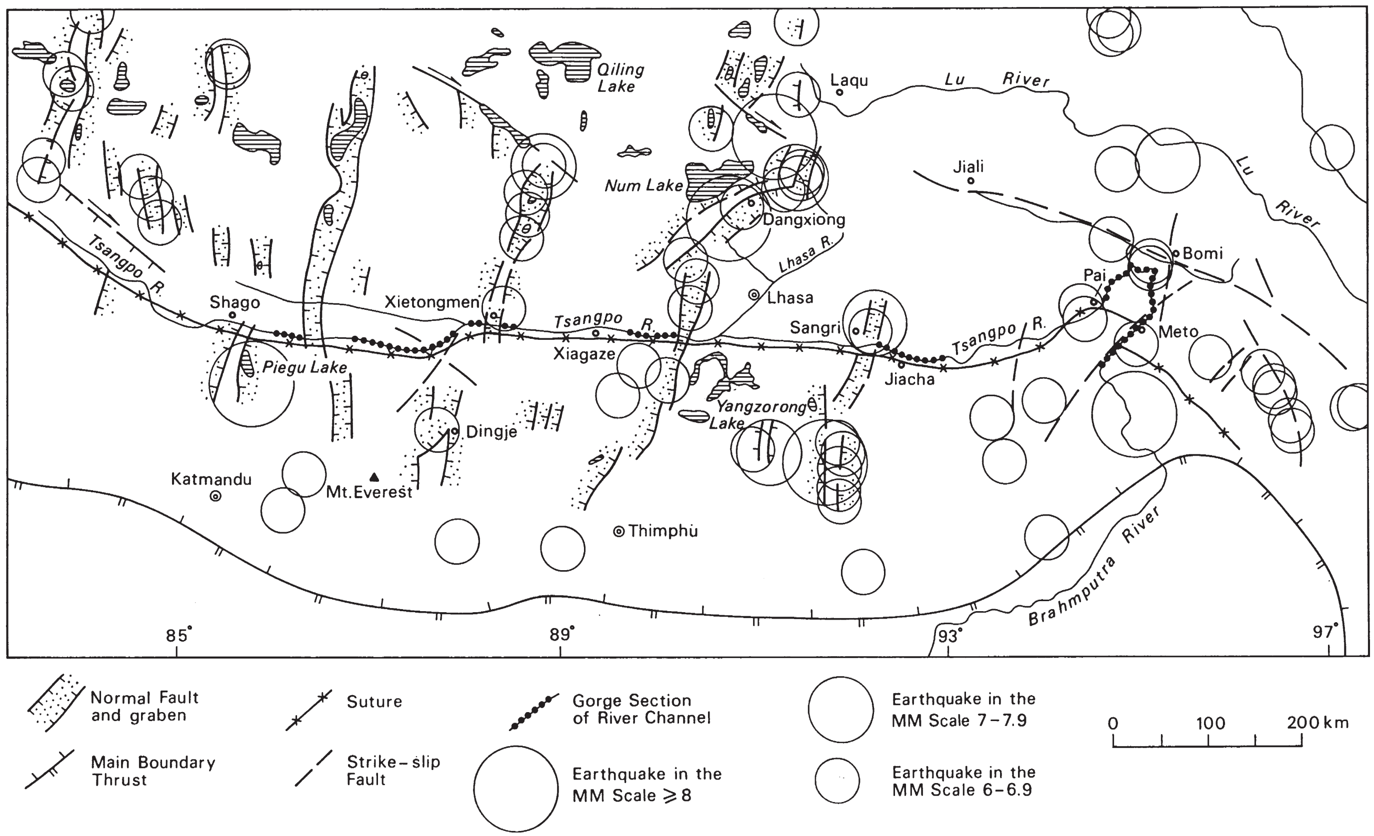

Figure 1. Active tectonic structures and major rivers in southern Tibet (based on Xiao *et al.*, 1988)

anastomosing channels with wide valleys are separated by single straight and deeply entrenched meandering channels with gorges. The river's long profile is also 'abnormal', with gentle profiles on the upstream and middle reaches, and a steep profile downstream.

The existence of the river first became known to western geographers through D'Anville's maps, which were compiled from surveys made at the beginning of the eighteenth century by Chinese Lamas (Burrard and Hayden, 1907). However, the identity of this great river with the Brahmaputra was not finally confirmed until 1880 by the exploration of Pandit Kishen Singh (Montgomerie, 1885). In the early decades of this century, a number of geographers (Burrard and Hayden, 1907; Hedin, S. 1917; Ward, 1934; Pranavanada, 1939) studied the river, but many questions remained unanswered because of the difficult access. In the 1950s, 1970s and 1980s, the Chinese Academy of Science and the Geological Ministry of Chinese Government organized a series of expeditions to Tibet. A group of geomorphologists from Chinese research institutions and universities studied the Tsangpo River and its tributaries. Their work mainly involved survey of valley form, terraces, river channels and the evolution of the river (TETCAS, 1983). The work provided much descriptive information on the fluvial landforms, but there are still many unexplained phenomena and unsolved geomorphological problems of the Tsangpo River on this the largest, highest and youngest plateau in the world. Since the 1980s, a series of international geological expeditions to Tibet have been carried out, which enriched our knowledge of the plateau tectonics. Some landform studies in the region have also been carried out by Seeber and Armbruster (1983), Sweeting *et al.* (1991) and Zhang (1991, 1994, 1996a). Having undertaken several expeditions to Tibet, the author believes that these problems could be solved on the basis of detailed geological, geomorphological and sedimentary investigations.

GEOLOGICAL HISTORY AND PREVIOUS GEOMORPHOLOGICAL HYPOTHESES

According to the recent geological evidence, the tectonic movements associated with the uplift of the plateau can be divided into three phases (Dewey *et al*., 1988). These can be generalized roughly in order as: the thrust and north–south shortening phase; the strike-slip phase; and finally the fast uplift and east–west extension phase.

The first phase started with full contact between the Indian subcontinent and the Eurasian Plate. The collision between the leading edge of Great India and South Tibet (Lhasa Terrain) was probably well established between 55 and 50 Ma ago along the Indu-Tsangpo Suture, based on sedimentological, structural and palaeomagnetic data (Powell and Conaghan, 1972; Burg *et al*., 1984; Patriat and Achache, 1984; Klootwijk *et al.*, 1985; Powell, 1986/7; Windley, 1988; Coward *et al*, 1988; Searle *et al.*, 1988; Burg, 1993; Searle, 1995). Powell (1986/7) considered that the Middle Eocene to Early Miocene was a time of subdued relief and tectonic quiescence. A mid-Eocene marine transgression covered many parts of India and extended as far north as the Indus–Tsangpo Suture. During this time a thick molassic unit was deposited on the south flank of the Gandise Ranges, which is where the Tsangpo River develops. Most of India was covered by laterites and some parts were karstified, while in north Tibet the widespread Tanglha erosion surface developed (Zhang *et al.*, 1981).

The second main tectonic phase started in the Miocene, with subduction of continental crust along the Main Central Thrust (MCT). A newly formed intercontinental shear probably began around 20 Ma as indicated by isotopic dating of biotite and muscovite to 30–10 Ma and 25–13 Ma (Mehta, 1980). The strike-slip faults led to a shortening of the intercontinental part of Tibet and often cut off the previous east–west structures. Due to the eastward escape of these faults, the fault blocks of the southeast part of the Nyainqentanglha, including the Lhasa area, subsided relative to the areas to the north and west. The Thakkhola graben in the Southern Tibetan Plateau also produced comparable eastward extension before 14 Ma ago (Coleman and Hodges, 1995). The present shape of the Himalayas developed during this phase, because major mid-Miocene thrusting along the Himalayas occurred about 16±2 Ma ago (Sharma *et al.*, 1978). Therefore, the Miocene may be considered as a period of strike-slip faulting with a certain amount of uplift.

The Pliocene was regarded as the beginning of the third phase with extremely active tectonic movement. The latest evidence shows that many north–south grabens with thick Pliocene sediments formed as the extreme east–west crustal extension began 5 Ma ago in Tibet, a minimum of 50 km of eastward extension from Tibet being indicated by the 10 mm a^{-1} east-west extension (Dewey *et al*., 1988). This was accompanied by the

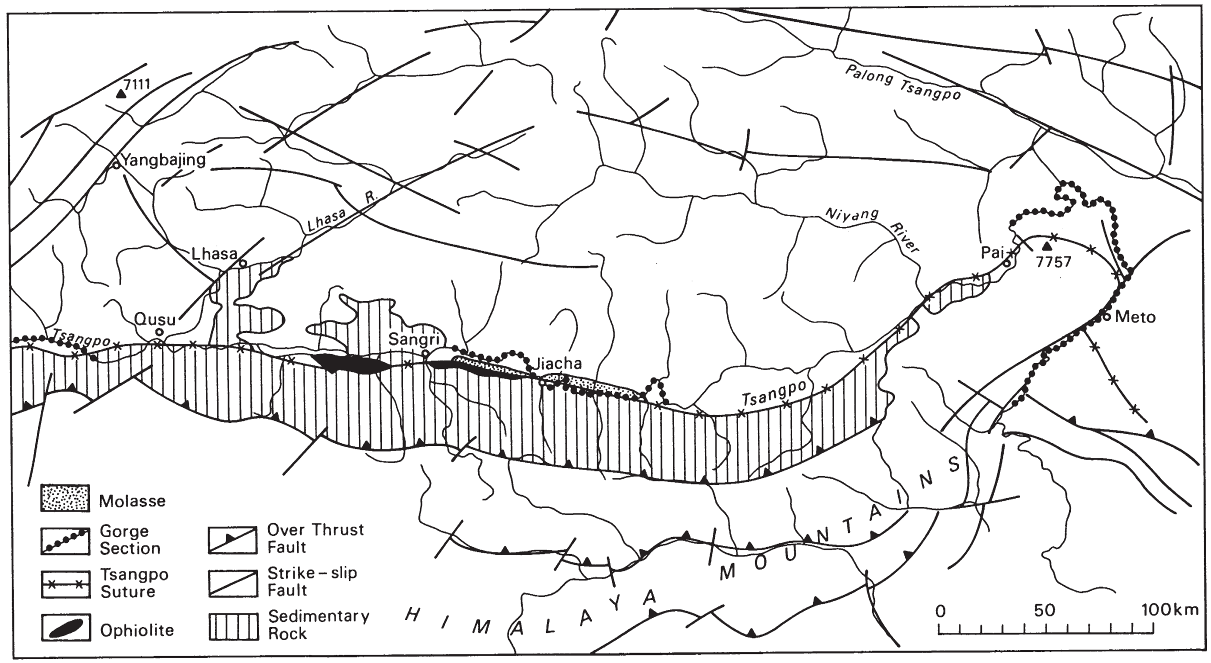

Figure 2. Pre-Pliocene tectonics and the distribution of sedimentary rocks in the eastern section of the Tsangpo

occurrence of widespread Pliocene and Quaternary normal faults and volcanism throughout the province (Fig.1). Most of these faults are still active, with the appearance of hot springs and frequent occurrence of earthquakes. The normal faults also cut through the shear structures and the pre-Miocene east–west structures. Some of the strike-slip faults were reactivated and changed into normal faults because of the east–west extension. Meanwhile, from the Tethys Himalayas to Northern Tibet, the whole plateau has been rapidly uplifted since 3·4–3 Ma (Wen, 1997). Sediments deposited on the south slopes of the Himalayas imply that uplift has accelerated since 800 ka. As the uplift is in the form of whole-plateau elevation, the internal plateau was not influenced by accelerated headward erosion from the plateau edge at the initial stage. A wide Pliocene valley formed along the Tsangpo River and its tributaries (Zhang, 1991). This tectonic movement has been continuing into the Holocene. During this period, the Pliocene cool and moist climate of the plateau has changed into the present arid and cold climate (Manaba and Terpstra, 1974; Hahn and Manaba, 1975; Ji *et al.*, 1981; Lin and Wu, 1981, Xu, 1981; Molnar *et al.*, 1993).

Although the geological structures of the Tibetan Plateau are very complicated, most large neotectonic structures produced in the river's drainage can be attributed to one of the three phases of the tectonic movement discussed above. Generally, the east–west thrusts, reverse faults and folds belong to the structures of the first phase; shear faults occurred in the second phase and normal faults were produced due to the east–west extension in the last phase (Figures 1 and 2).

The middle section of the Tsangpo River starts from Shago and ends at Pai. The river valley basically follows the Tsangpo Suture and outcrops of ophiolite can be seen at various places. The river's course consists of alternating wide valleys and gorges, with steep gradients in the gorge sections and gentle slopes in the wide valley sections. These alternations of gorge and wide valley were explained by some geomorphologists largely as the result of rock resistance, with hard granite rocks in the gorge sections and soft sedimentary rocks in the wide valley sections (TETCAS, 1983). The river terraces in the gorge sections are generally higher than those in the wide valley sections, a difference which TETCAS (1983) attributed to the blockage by diluvial fans, glacio-fluvial deposits, and rockfalls in the gorge sections, and to river discharge changes.

In the wide valleys, a lot of lacustrine terraces and sediments have been discovered, but their origin and significance are disputed. Some scientists believed that the blockage of the river by glacial, diluvial, landslide and glacio-fluvial sediments in the gorge sections caused the formation of the lakes in the wide valleys (TETCAS, 1983; Han, 1984). Others thought that the interior lakes were original forms in a series of enclosed basins along the suture, the lakes being captured by the headward erosion of the Brahmaputra, finally creating this river in the Middle Pleistocene (Fong, 1957). Some geomorphologists consider that there are three knick points developed at Pai, Jiacha and Shago along the river's long profile. The knick points were believed to indicate three stages of uplift in the Quaternary Himalayan Movements (TETCAS, 1983).

The river channel form varies from single channel to meandering and braided channels and the distribution of the channel forms is 'abnormal'. Braided and anastomosing channels can be found in the upper stream, and single and straight channels downstream. As early as 1907, Burrard and Hayden (1907) had already found a problem in the flow direction of the river's main tributaries: there is a tendency for some tributaries to flow in a direction opposite to that of the main trunk. Consequently they argued that the river must have flowed from east to west at some time in the past.

The above hypotheses, which interpreted the intriguing geomorphological problems of the Tsangpo River, were presented before the concept of plate tectonics was introduced into China and applied to Tibetan landform development. Therefore, there is a great need to test these hypotheses by looking in detail at the geology, geomorphology and sediments of the river's drainage basin and whole plateau.

RESEARCH METHODOLOGY

Because the river basin has such complicated geological structures and types of rock, published geological information is not sufficient for this study. Based on the geological map with 1:1000000 scale, which was published by the Ministry of Geology and Minerals of the PRC, new geological investigations were focused on neotectonic structures and rock types in the river basin, especially the active faults across the river channel,

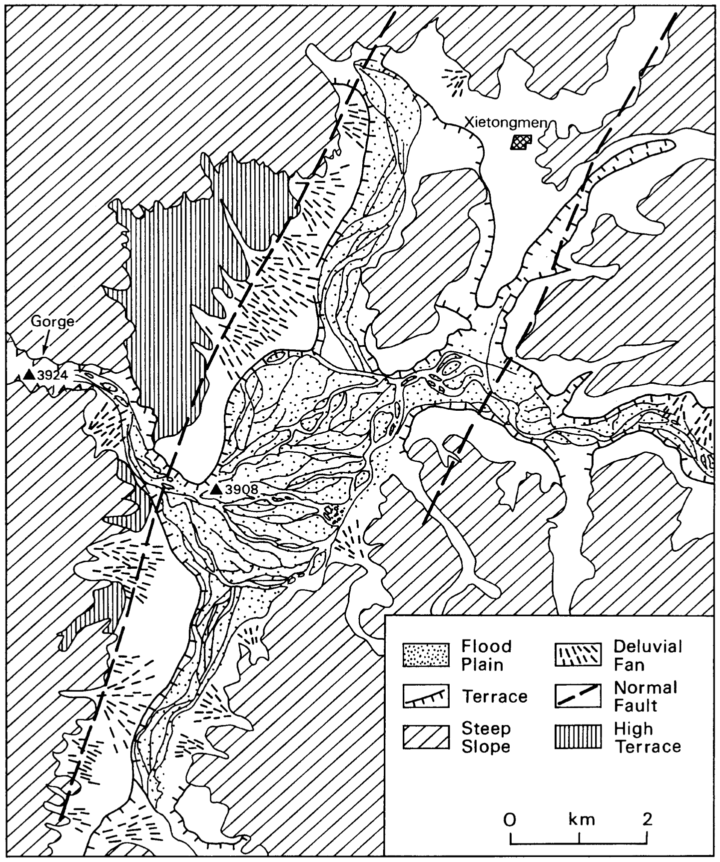

Figure 3. Wide valley and braided channel caused by active faults in the Xietongmen Graben (based on the Chinese Military Ordnance Map, 1:100 000)

because the author believes that the neotectonics is a very important factor controlling the formation of the Tsangpo fluvial landforms.

Geomorphological fieldwork was carried out during three expeditions to Tibet in 1987, 1988 and 1996. These concentrated on the main course and two of its main tributaries, the Rivers Lhasa and Nienchu. Fieldwork included measurement of terrace elevation and sedimentary profiles, and observations of terrace, valley and channel forms. This study also included analysis of 1:200 000 and 1:100 000 scale ordnance maps of the Chinese army. Morphological and elevation changes of valley, channel and catchment along different sections of the river were compared in order to identify the differences that could be related to neotectonics. The maps were also used to locate geological features in the middle stream areas. Further mapping has been carried out.

Sediment profile and sedimentary analyses were carried out in order to test the findings from geological and geomorphological investigations. The sediment samples were brought to the laboratories in Manchester, Oxford, McMaster and Hong Kong Universities. Grain size, chemical and mineral analyses and ^{14}C and U-series dating techniques have been applied to the river sediments to identify their age, sources, depositional processes and degree of weathering.

GEOLOGICAL STRUCTURES AND THE RIVER

On the geological map (Zhou *et al.*, 1984), the river valley can be seen to develop along the Tsangpo suture, with ophiolite found in wide valleys. Many small tributaries and some of the large tributaries flow in a south–north direction to the central main stream. The strike-slip faults caused by shearing are common on the Plateau and

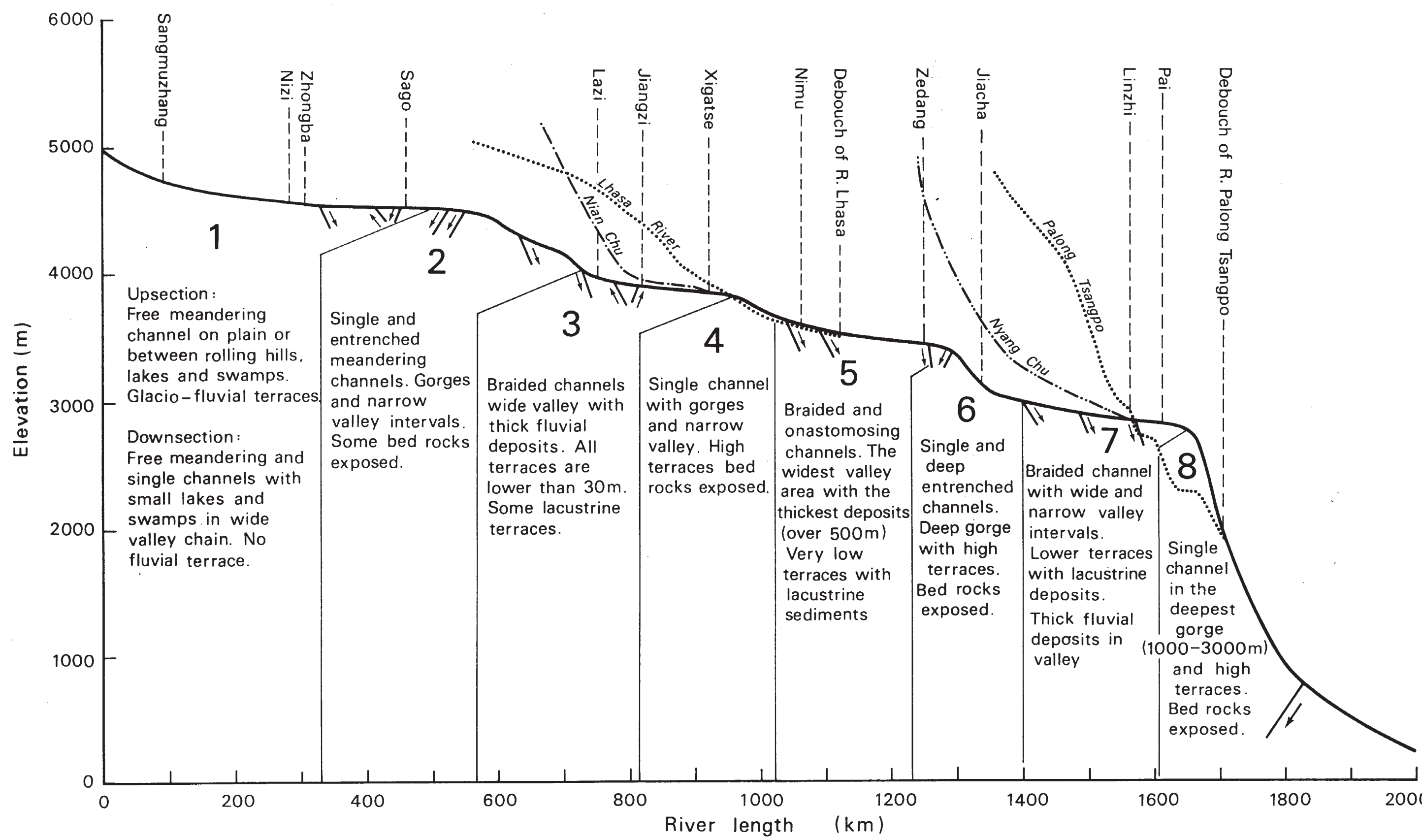

Figure 4. Longitudinal profile and the river sections with related fluvial landforms of the Tsangpo River

they often cut across the east–west thrusts. They control the orientation of some large tributary courses, such as the Lhasa, Nianchu and Palong Tsangpo (Figure 2). The Lhasa and Nianchu flow in a direction opposite to that of the Tsangpo. During the geological fieldwork, the author found more strike-slip faults along the Lhasa River valley and its tributaries, and the whole drainage system of the river exhibits a rectangular pattern (Figure 2).

Geological investigations were focused on the places where the sudden changes of fluvial landforms occur along the middle reach. According to the information provided by other geologists (Zhou *et al*., 1984, Liu *et al.*, 1988; Dewey *et al.*, 1988), the author found that most boundaries between gorges and wide valleys are related to the active faults. A typical sample is in Xietongmen, where there is a graben cut across the river (Figure 3). Developing diluvial fans along the fault lines reflect the fact that uplift on the upthrown side of the faults is very rapid. The faults also form the boundary between different landform types. On one side of the active faults lies a wide valley containing a braided river channel along with thick fluvial deposits and a gentle hydrological gradient; on the other is a single, straight, deep gorge with rapidly flowing water.

It is important to examine the stratigraphy along the river valley in order to understand the valley form and hydraulic gradient problems. From Pai to Nang Xian, the river course with a wide valley is mainly developed in the regional migmatite and migmatic granites. In the following gorge section, a sedimentary–melange complex and molasses appears downstream, and granites occur in the upper part of this section (Figure 2). From Sangri to Xietongmen the river course passes through granites, sedimentary–melange complex, molasse, and an ophiolite suite. From Xietongmen to the end of the middle reach of the river, the sedimentary–melange complex and flyschoid association dominate this gorge section. The rocks with the strongest erosion resistance, granites, have a wide distribution in the basin and appear in both gorge and wide valley sections. Flysch, with a large proportion of thin-layer shales and marls, appears in the gorge section and these rocks build up steep slopes as well. So, the alternation of gorges and wide valleys, and of gentle and steep gradients is not explained by the variable resistance of lithologies, as suggested by TETCAS (1983). This is also inferred from other sites in tectonically active areas. Seeber and Armbruster (1983) also found that the relatively high gradients on the profiles of the transverse Himalayan rivers cannot be associated with differential resistance to erosion in all cases.

FLUVIAL LANDFORMS

Geological investigation along the middle stream of the Tsangpo shows that all sudden changes of fluvial landforms are closely related to the faults across the river. Thus, eight landform sections along the river main course can be demarcated by these faults, basically the wide valley sections and the gorge sections (Figure 4).

The wide valley sections generally are located on the downthrown sides of the normal faults and the gorge sections on the upthrown side of the faults. The average elevation of mountain summits on both sides of the wide valleys is about 5400 m, but those of the gorge sections are over 6000 m. This reflects the fact that the upthrown areas have been uplifted by at least several hundred metres.

Three knickpoints identified before are located at Pai, Jiacha and Shago. Downstream of Pai, there is a major shear fault that is related to the east extension of the Main Central Thrust (MCT). The fault cut off the Tsangpo Suture and caused the formation of the Lanjabama Mountain (7756 ma.s.l.), which is the east end of the Himalayas. The MCT is also responsible for the formation of the Himalayas. In recent years, earthquakes have frequently occurred in this area and many hot springs have been found in the gorge. The second knick point is related to the normal faults that cut across the river immediately downstream and upstream of Jiacha. At these sites, earthquakes and hot springs are common phenomena. The third knick point is developed at a point 100 km upstream of a normal fault (Figure 1). Very steep gradients and exposed rock river beds are common in the gorges, and their formation periods depend on the individual fault movement at a local scale, not on uplift stages of the whole plateau. Actually, steep gradients and bare rock river beds can be seen in any place where the normal faults cut across the river. These places could also be called knickpoints. Such knickpoints are always located at an upstream part of a gorge section, or just near its upper entrance, demonstrating that headward erosion has occurred since normal faulting. If the knick point in Shago (4500 ma.s.l.) represented the first stage of the Quaternary uplift, the uplift rate of the whole plateau would have been over 4000 m during the Quaternary. It is more likely that the knickpoint in Pai indicates the beginning of rapid uplift of the whole

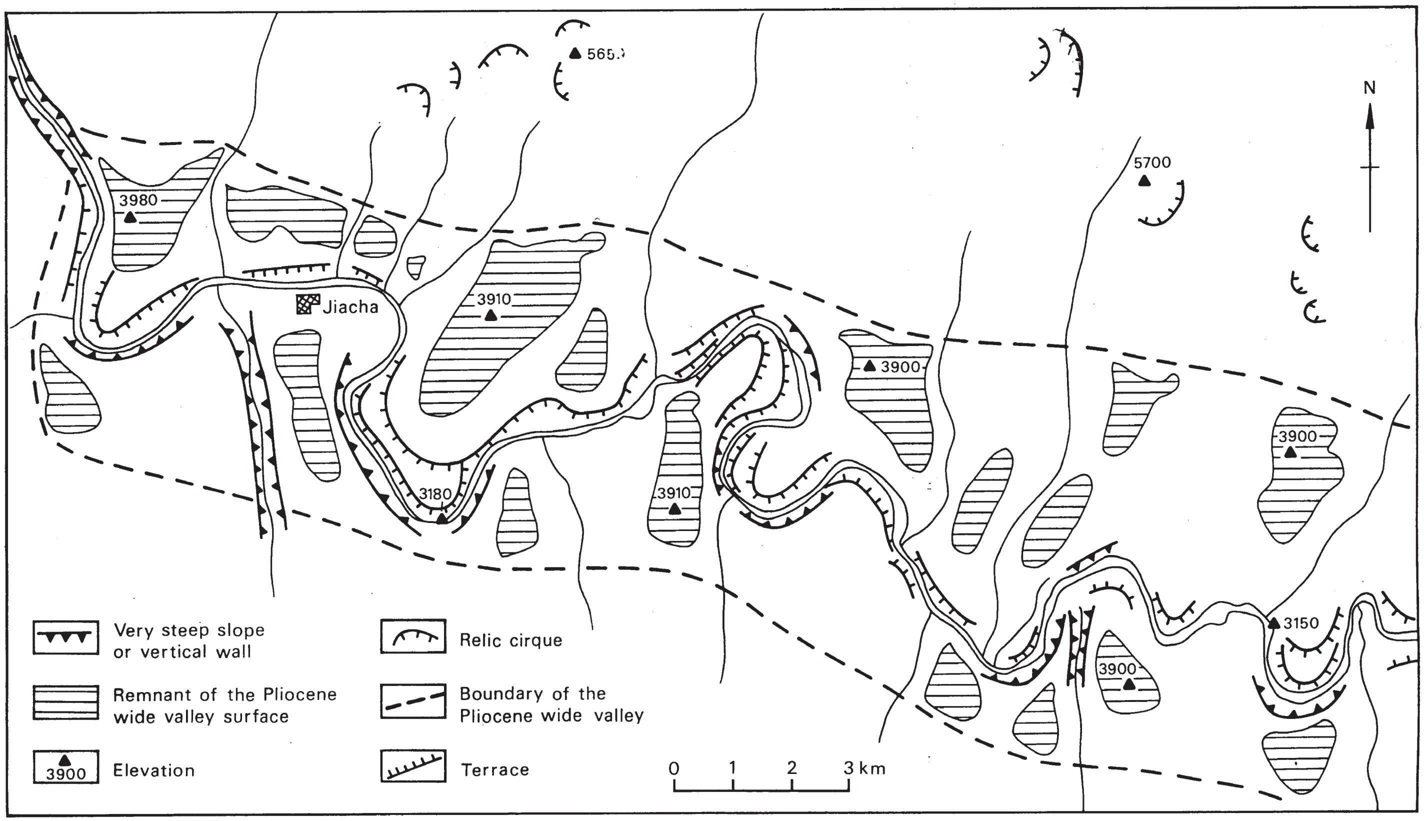

Figure 5. The deeply entrenched meandering channel at Jiacha (based on the Chinese Military Ordnance Map, 1:100 000)

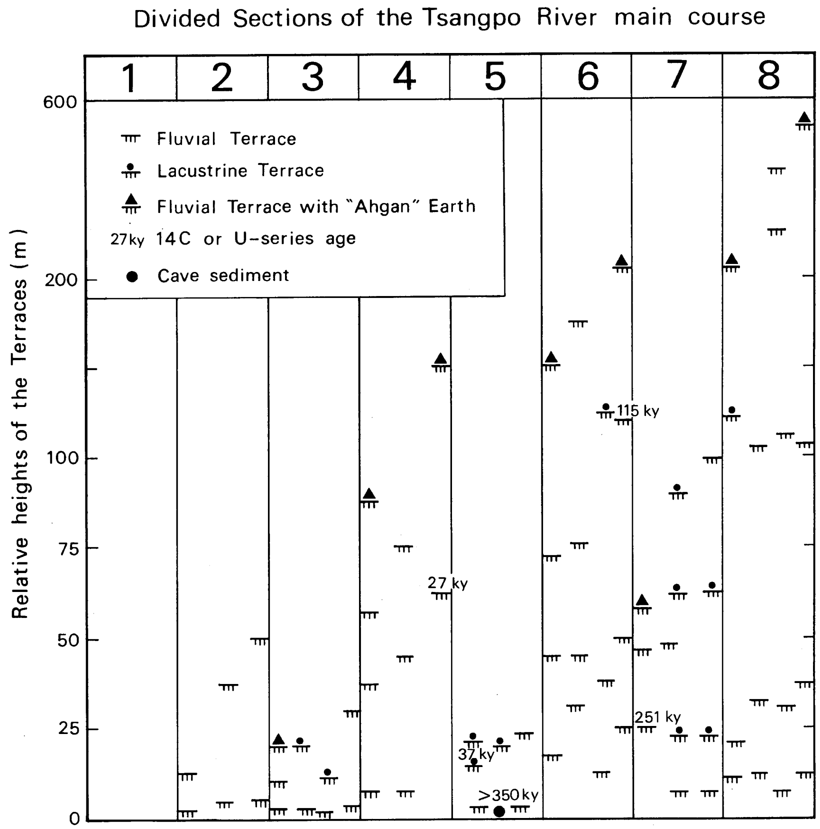

Figure 6. Terrace relative heights in the different sections of the Tsangpo River. Half of the terrace heights were measured by the author using tape and geological compass, others are based on TETCAS (1983).

plateau since the Pliocene, which corresponds to the uplift rates suggested by many authors (Sharma *et al.*,; Xu, 1981; Zhang, *et al.*, 1981, 1978; Zeitler, 1985; Zhang, 1991; Wen, 1997).

In the wide valley sections, the river channel form in the middle and lower reaches is dominated by braided channels and the width of the valley decreases from downstream to upper reaches. In these valleys, thick alluvial deposits cover the whole valley. These imply that the formation of the wide valleys is due to deposition on the downthrown sides of active faults. In the gorge sections, however, are mainly single and deeply entrenched meandering channels with bedrock in the riverbeds. The entrenched meandering channels indicate free meandering channels before rapid uplift of blocks, defined by active normal faults, caused deep incision. A typical example can be seen near Jiacha County, where the deeply entrenched meandering channel occupies over half the section length (Figure 5).

In the river valleys, the distribution of the terraces is scattered and variable in terms of relative heights in the different sections. This has confused many geomorphologists (TETCAS, 1983). In drawing up tables and trying to find the height relationships between the terraces, they found that differences are so large that the terraces cannot be compared to each other. They listed the factors that may explain the changes in the relative height of terraces. According to the investigations of the author, blocking of river flow by diluvial fans and glacial deposits can lift the water level up to 20–30 m above normal, while river regime contrast may lead to a maximum 10–20 m terrace difference in the gorge areas. Rock falls can bring about a certain amount of rise in terrace elevation, but they are temporary and local in effect. None of these factors, in the author's view, can

Table I. Clay mineral composition and SiO_2/Al_2O_3 ratios of the terrace sediments at various heights in the different sections

Sample no.	Sediment types	Relative height (m)	Section	Clay minerals (%)	SiO_2/Al_2O_3
Te308	fluvial	30	3	7·4	4·6
Te211	fluvial	20	3	6·8	4·7
Te311	lacustrine	16	3	none	7·6
Te432	lacustrine	6	3	none	7·9
Te186	fluvial	150	4	10·1	3·9
Te187	fluvial	87	4	11·2	3·7
Te188	fluvial	60	4	7·1	5·8
Te189	fluvial	8	4	7·5	8·1
Te314	lacustrine	20	5	none	7·4
Te298	fluvial	5	5	5·8	4·6
Te278	fluvial	210	6	12·1	3·4
Te279	fluvial	80	6	2·9	5·6
Te280	fluvial	50	6	1·9	5·6
Te322	fluvial	20	6	none	7·2
Te398	fluvial	100	7	6·4	5·4
Te374	fluvial	70	7	2·9	6·7
Te314	lacustrine	60	7	4·3	6·6
Te315	lacustrine	18	7	1·9	7·9

explain the large differences between terrace elevations (a 100 m minimum difference for terraces of the same age in different sections), nor solve problems of terrace height comparison.

The distribution of terraces and their elevations, which are based on the author's and others' fieldwork (TETCAS, 1983), can be rationalized in terms of the sections identified by the author (Figure 6), these being explained by block movements across the valley. In wide valleys, the terraces are low, and close to each other. In contrast, terraces in the gorges are higher, scattered and at greater height intervals. Many of them are bedrock strath terraces. The overall trend of terrace relative height in the whole river course is that they increase from upstream to downstream. In wide valley sections, because of the alluvial burying of the river valley, old terraces have been covered by fluvial sediments and/or remain at low levels. The rapidly uplifted blocks have been incised by the river and their original terraces have been elevated to higher positions in the newly formed gorges (Figure 6). Compared to the early Pleistocene terraces in different sections, the relative elevations of older terraces in uplifted blocks are higher, or much higher, than in lowered blocks. In Section 5, no terrace higher than 25 m and older than the late Pleistocene has been found so far, even by intensive survey. In this section, the highest or oldest terraces are covered with the late Pleistocene lacustrine sediments and the low terraces were formed by older fluvial deposits. If we examine the individual sections, the terrace relative heights are also different from their upper and downstream reaches. In the gorge sections, the relative heights increase from the downstream reach to the upper reach, also indicating that headward erosion started at the place of the base level descending, which is where the normal faults occurred. In wide valley sections, although they have the same tendency, the ages and types of the sediments are quite different. This will be discussed in the next section.

SEDIMENTARY EVIDENCE

According to the above studies on the river's geology and geomorphology, it is suggested that the formation of the alternating sections of wide valleys and gorges, large difference in terrace heights, formation of palaeolakes, and abnormal distribution of channel forms of the middle reaches are the results of normal faulting. This hypothesis can be tested by some sedimentary evidence.

As the climate of Tibet has gradually changed into cold and arid since its uplift, the degree of weathering of sediments, which can be examined by mineral and chemical composition, may reflect their relative ages. The results of mineral and chemical compositions of the terrace sediments at different relative heights and various positions are shown in Table I. A relatively large percentage of clay minerals has been found in high terrace sediments in the gorge sections, compared with only a small percentage, or even no clay minerals, in their lower terrace sediments. This indicates that the relative age distribution is normal according to the terrace sediment heights. However, clay mineral contents in low fluvial terrace deposits in the gorge sections are lower than those

of fluvial sediments in the low terraces of the wide valleys. The ratios of Si_{2O}/Al_2O_3 exhibit the same trend. This suggests fluvial terraces in the wide valleys are older, even though they are similar in terms of relative heights. So-called 'Ahgan Earth', being a local name for red mild clay with calcareous concretions, dated as early Pleistocene and used by local people to make pottery (TETCAS, 1976), often occurs on the highest terraces in the gorges, but in the wide valleys it appears in upstream low terraces or is absent (Fig. 6), probably due to burial by alluvial deposits in the downstream and middle stream sections of the wide valleys. Therefore, the difference in relative ages between terraces of similar height is most likely caused by the relative movement of the blocks.

Application of dating techniques further supports the above analyses. At 20 km downstream of the boundary between Section 4 and 5, a piece of wood from the 15 m high terrace with lacustrine sediments was dated by ^{14}C (in South China Marine Research Institute) to 37 000±6 000 BP. However, 10 km upstream from the boundary, the ^{14}C age of a piece of animal fossil in the sediments of a 65 m high gorge terrace has an age of 27 000±3, 400 BP. A late Pleistocene animal fossil dated by ^{14}C (TETCAS, 1983) was also found on the 80–90 m high terrace on the gorge section (Section 4). This demonstrates relative movements between fault blocks in recent geological time. The U-series dates of animal fossils and calcium carbonates from the section 6/7 boundary also suggest a young terrace lying higher than an older terrace (Figure 6). U/Th ages of >350 000 years (probably >1.25 Ma: Zhang 1996a) from speleothems which developed within the fluctuation range of cave water level on the floor of a cave just 2 m above Lhasa River water table (Zhang, 1991), about 20 km from the junction of the Tsangpo in the same wide valley of Section 5, indicates the wide valley is a buried valley because these speleothems are only produced in the vadose zone.

In the wide valley sections, lacustrine sediments are widespread and older fluvial terrace sediments are rare in their lower reaches. The lacustrine sediments are very thick at the downstream ends of the valley; however, some old fluvial terraces exist and lacustrine sediments are rare or absent at the upstream ends of the valleys. This indicates that the palaeolakes were initiated at the downstream end of the wide valley, where it was blocked by the uplifted block. In Section 7, three layers of lacustrine sediments are interbedded with fluvial sediments, indicating at least three formation periods of palaeolakes in this section.

The thickness of the river bed sediments in the wide valleys may provide evidence to support the hypothesis that blockage of uplifted blocks caused deposition at the wide valleys. Unfortunately there is a lack of borehole information in the wide valleys of the main course. However, in the Lhasa wide valley, which is connected with Section 5, geophysical survey has revealed 480 m of sediments in the river bed (the Second Geological Team of Tibet, 1977). According to the valley width and old terrace distribution, a conservative estimate of the thickness is over 500 m at the downstream end of Section 5. Such a great thickness of sediments cannot be created by river regime changes and blockage by landslides, glacio-fluvial sediments and diluvial fans, but could suggest that Section 6 has been uplifted by at least 500 m.

At an elevation of 3800 m in the Pliocene palaeovalley surface in Section 7, higher than the Ahgan Earth deposits, a layer of cemented pebbles contains marine clastic limestone that is only exposed upstream. Thus, the direction of river flow in the Pliocene can be considered the same as the present-day (cf. Burrard and Hayden, 1907). Mean grain size of the lacustrine sediments on the highest terraces in Section 7 gradually increases upstream (Table II), as in modern reservoir deposits, implying that the palaeolakes were not interior lakes, as suggested by Fong (1957), but were connected with the river drainage system, and the flow direction was to the East. The drainage of these palaeolakes may indicate that incision has overtaken uplift, so that the river cut into the lacustrine deposits and the lacustrine terraces were left in the wide valleys. Some new fluvial terraces may be found at very low elevations, often as a result of river incision after the palaeolakes disappeared. The incision also caused new terraces to form on the old fluvial sediments that underlay the lacustrine sediments (Figure 7).

CONCLUSIONS

Based on the above investigations, solutions to some of the geomorphological problems of the middle reach of the Tsangpo River consist of the following.

1. The formation of alternating sections of wide valley and gorge in the middle reach of the Tsangpo River is caused by the third phase of neotectonic movements (Pliocene). Normal faults induced by east–west

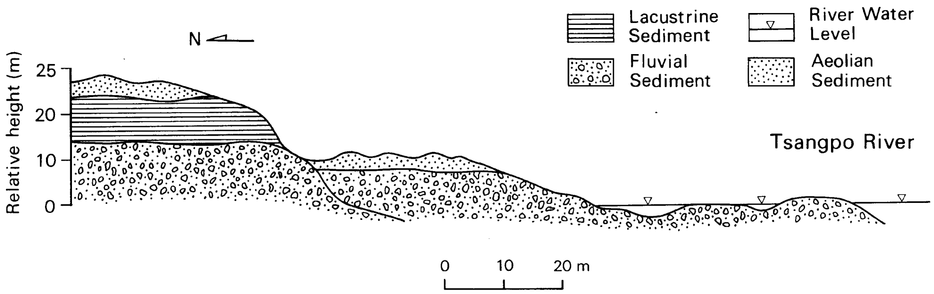

Figure 7. New fluvial terrace on old lacustrine sediments near Sangri in Section 5

Table II. Mean grain sizes of the lacustrine sediments in Section 7

Sample no.	Relative height (m)	Distance to Pai (km)	Mean size (mm)
Te314	60	28	0·0110
Te345	55	45	0·0109
Te356	31	63	0·0171
Te357	25	70	0·0267

extension in the internal plateau cut across the river and formed a series of new local base levels. Deposition occurred on the downthrown sides and strong erosion was induced in the uplifted blocks. The uplifted blocks on one or more occasions blocked the river in the middle stream and led to the formation of palaeolakes in the deposition sections. These palaeolakes disappeared in the late Pleistocene because the uplift of the rising blocks slowed down or the rate of river incision accelerated. Rock resistance seems to be a minor influence on valley forms and gradients, as the hard rocks exist in the wide valleys and soft rocks are exposed in the gorges along the river.

2. In the gorge sections, the river gradients generally are greater than those in the wide valleys, and rock outcrops can been seen in most of the riverbed in the gorge sections. This indicates that erosion is very active in these sections. The active erosion was caused by the changes of local base levels, which are also due to active fault movements. It is unlikely that knick points in these gorges are the result of the headward erosion caused by whole-plateau uplift; rather they reflect local tectonic movement in most cases. It is very doubtful that the three steep gradients on the long profile can represent three uplift stages of the Quaternary Himalayan movements because these local faults occurred in the same phase of tectonic movement. The precise times of faulting are still unknown.
3. The relative movements of the blocks across the river cause confusion in comparison of relative terrace heights along the river. Dating of terrace sediments shows that fault movements were still active during the middle to late Pleistocene. However, once the vertical throw of the faults and the dates of the terrace sediments are known, the evolution of these river valleys can be established.
4. The single straight and deeply entrenched meandering channels in gorge sections were formed by uplift of the fault blocks under the river valley. The relative depression of blocks brought about the formation of braided and anastomosing channels. The free meandering channel that is produced in the upper stream area does not form in the middle stream. The explanation for this is that the middle stream has a higher hydraulic gradient, which may be induced by the headward erosion from the gorge sections.
5. Only two out of ten major tributaries flow in a direction opposite to that of the main stream. Both of these rivers are controlled by strike-slip faults and cannot be used as evidence of the original flow direction of the Tsangpo River. The river was already flowing east at least by the Pliocene. The direction before this time is difficult to estimate because the older erosion surfaces have been destroyed.

In summary, neotectonic movements of the Tibetan Plateau control development of the fluvial landforms in the middle reach of the Tsangpo River. The third phase of movement is the most important controlling factor in the formation of many of the fluvial features in the river valley. However, more precise dating of the formation

of the palaeolakes, normal faulting and most of the terraces will be required in order to improve our knowledge of the palaeo-environments and river processes of the Tibetan Plateau.

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